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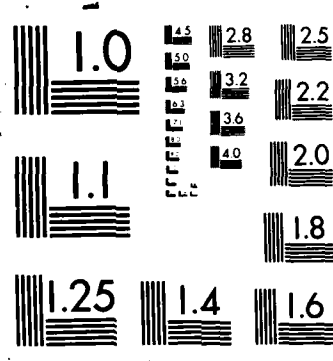
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THE FRAM CAVITATION CODE

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15 May 1986

Technical Report

CONTRACT No. DNA 001-84-C-0001

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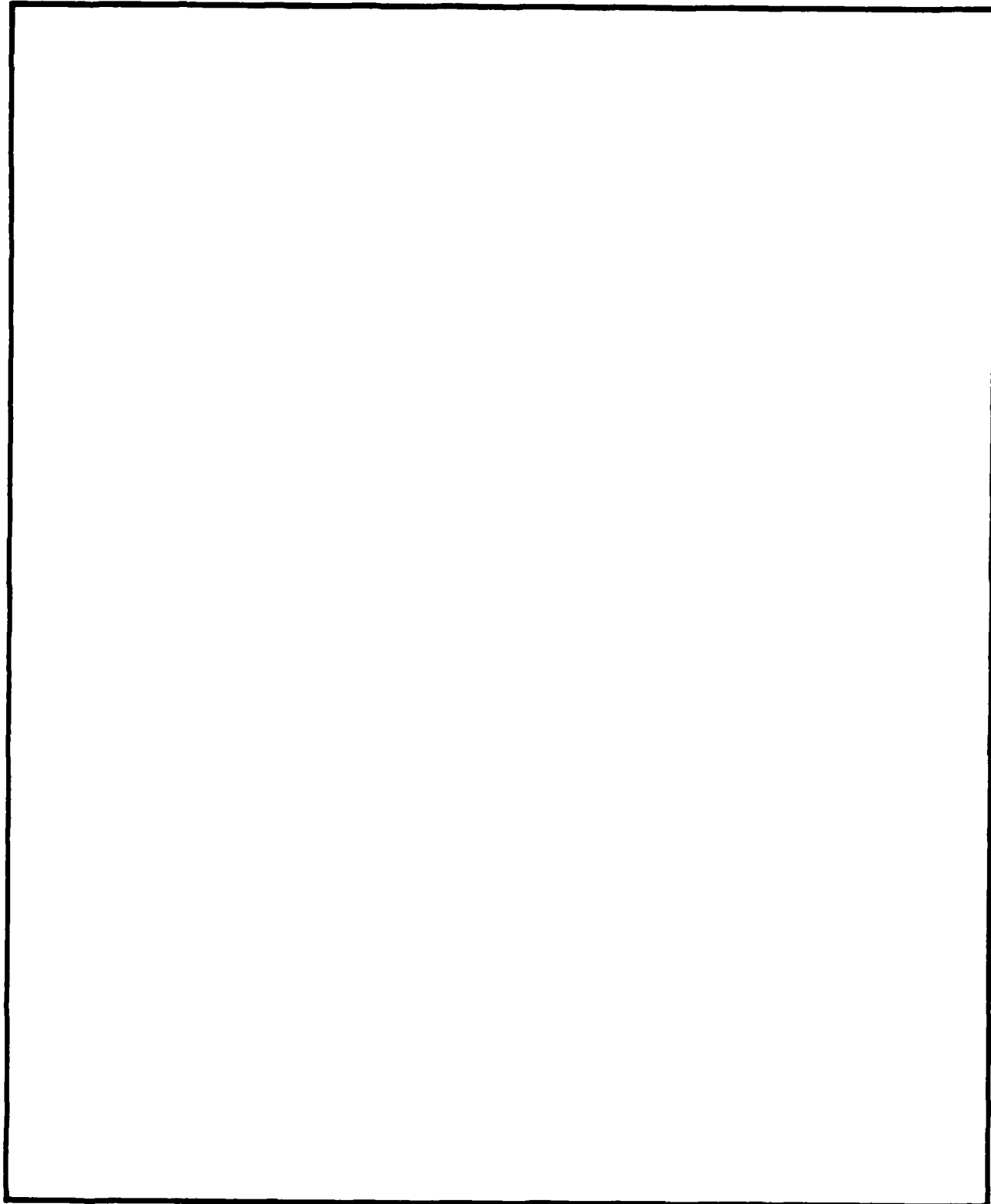
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| 19 ABSTRACT (Continue on reverse if necessary and identify by block number) This report describes the computer code FRAM. The code computes the pressure and velocity in a fluid-half space where bulk cavitation may occur. The cavitation results from an exponentially decaying pressure wave from an underwater explosion which travels to the surface and is reflected as a tension wave. Because the water does not sustain tension, a cavitated region is formed. The cavity subsequently closes under gravity (lower closing shock) and accretion of vapor particles (upper closing shock). The theory is summarized herein. Capabilities and limitations are discussed and a description of the source code is included. | | | | |
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CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement.

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TO GET \longleftarrow BY \longleftarrow DIVIDE

| | | |
|---|-----------------------------------|---|
| angstrom | 1.000 000 X E -10 | meters (m) |
| atmosphere (normal) | 1.013 25 X E +2 | kilo pascal (kPa) |
| bar | 1.000 000 X E +2 | kilo pascal (kPa) |
| barn | 1.000 000 X E -28 | meter ² (m ²) |
| British thermal unit (thermochemical) | 1.054 350 X E +3 | joule (J) |
| calorie (thermochemical) | 4.184 000 | joule (J) |
| cal (thermochemical)/cm ² | 4.184 000 X E -2 | mega joule/m ² (MJ/m ²) |
| curie | 3.700 000 X E +1 | giga becquerel (GBq)* |
| degree (angle) | 1.745 329 X E -2 | radian (rad) |
| degree Fahrenheit | $T = (t^{\circ}F + 459.67) / 1.8$ | degree kelvin (K) |
| electron volt | 1.602 19 X E -19 | joule (J) |
| erg | 1.000 000 X E -7 | joule (J) |
| erg/second | 1.000 000 X E -7 | watt (W) |
| foot | 3.048 000 X E -1 | meter (m) |
| foot-pound-force | 1.355 818 | joule (J) |
| gallon (U.S. liquid) | 3.785 412 X E -3 | meter ³ (m ³) |
| inch | 2.540 000 X E -2 | meter (m) |
| jerk | 1.000 000 X E +9 | joule (J) |
| joule/kilogram (J/kg) (radiation dose absorbed) | 1.000 000 | Gray (Gy)** |
| kilotons | 4.183 | terajoules |
| kip (1000 lbf) | 4.448 222 X E +3 | newton (N) |
| kip/inch ² (ksi) | 6.894 757 X E +3 | kilo pascal (kPa) |
| ktap | 1.000 000 X E +2 | newton-second/m ² (N-s/m ²) |
| micron | 1.000 000 X E -6 | meter (m) |
| mil | 2.540 000 X E -5 | meter (m) |
| mile (international) | 1.609 344 X E +3 | meter (m) |
| ounce | 2.834 952 X E -2 | kilogram (kg) |
| pound-force (lbf avoirdupois) | 4.448 222 | newton (N) |
| pound-force inch | 1.129 848 X E -1 | newton-meter (N·m) |
| pound-force/inch | 1.751 268 X E +2 | newton/meter (N/m) |
| pound-force/foot ² | 4.788 026 X E -2 | kilo pascal (kPa) |
| pound-force/inch ² (psi) | 6.894 757 | kilo pascal (kPa) |
| pound-mass (lbm avoirdupois) | 4.535 924 X E -1 | kilogram (kg) |
| pound-mass-foot ² (moment of inertia) | 4.214 011 X E -2 | kilogram-meter ² (kg·m ²) |
| pound-mass/foot ³ | 1.601 846 X E +1 | kilogram/meter ³ (kg/m ³) |
| rad (radiation dose absorbed) | 1.000 000 X E -2 | Gray (Gy)** |
| roentgen | 2.579 760 X E -4 | coulomb/kilogram (C/kg) |
| shake | 1.000 000 X E -8 | second (s) |
| slug | 1.459 390 X E +1 | kilogram (kg) |
| torr (mm Hg, 0°C) | 1.333 22 X E -1 | kilo pascal (kPa) |

* The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

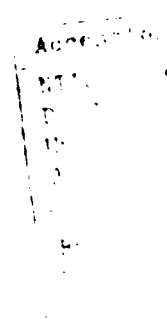
**The Gray (Gy) is the SI unit of absorbed radiation.

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SECTION 1

CAPABILITIES OF FRAM

FRAM (No acronym) is a computer code which computes the pressure and the velocity of a particle in a fluid half space where cavitation may occur. The cavitation is assumed to result from an exponentially decaying compression wave which travels to the surface and is reflected as a tension wave. Because the water does not sustain tension a cavitated region is formed. The cavity subsequently closes under gravity (lower closing shock) and accretion of vapor particles (upper closing shock).

The model of the fluid and the mathematical method used to determine the boundaries of the cavitated region are described in ref [1]. FRAM computes the *free-field solution*, that is, the field variables when no structure is present. The problem of the interaction with a floating structure requires the use of an approximate interactive scheme such as the plane wave approximation (*P.W.A.*) or the doubly asymptotic approximation (*D.A.A.*) in ref. [1].

FRAM does not treat bottom reflections and requires the explosion to be located a great distance away from the observation point in order to approximate the spherical waves by plane waves. It treats the incident wave as plane and steady state with respect to a system of coordinates moving with the wavefront.

The one dimensional characteristics method is used. It is applied to the two dimensional problem by transforming coordinates (X, Y, Z, T) into (y, ξ) where $y = Z, \xi = \sqrt{(X^2 + Y^2)} + sT$. Combining two or three parameters into ξ is done under the steady-state assumption that the cavity is unchanged with respect to a coordinate system moving with the apparent wave speed (s). Conservation of momentum and continuity of velocity across the closing shocks together with characteristic relations form the governing system of equations.

The analytic solution provided by FRAM has the advantage over numerical methods that is that it requires comparatively small computer resources and sharper wave fronts are obtained. The shortcomings result mainly from the inability to include bottom reflection effects and the divergence and decay associated with propagation away from the explosive source.

SECTION 2

DESCRIPTION OF THE CODE

2.1 PROGRAM ORGANIZATION.

Given the parameters of the explosion and of the fluid, the first step consists in finding the geometry of the cavitated region. Along with the geometry, pressure and velocity on the boundary are also computed. The second step takes the coordinates (y, ξ) of a point of observation in the fluid and computes its pressure and velocity. This is repeated for each time increment to construct a time history.

The main program calls the subroutine CAVITY which computes the geometry of the cavitated region. It is formed by three curves: AB , BC , AC (see figure 1, section 3). Having charted the geometry and physical properties of the free-field, one can proceed with the determination of the properties of a point of interest. Subroutine ECHO takes the coordinates of the point, finds its location with respect to the cavity using subroutine ZONE, and finally computes pressure and velocity at that point. Finally functions G and GG correspond to the characteristic functions g and to its derivative g' along the Y axis.

There are two types of parameters that must be specified: those pertaining to the material properties (c speed of sound in water, p_A atmospheric pressure, γ_0 fluid density, g gravitational acceleration) and to the explosion (L decay length, p_s peak pressure, β decay constant), and the coordinates (y, ξ) of the points of observation. All parameters and variables are given in a non-dimensional formulation. In the example, U.S. customary units are used. The output of the program consists in the curves AB, AC, BC forming the cavity, and in time histories of p, m, n .

2.2 DESCRIPTION OF SUBROUTINES.

The present version of the code is designed to interact with the finite element code SAP. A model for a ship provides the location of the wet nodes at which pressure and velocity histories are computed and input into SAP. The SAP input is read from tape 14 and written on tape 9. It is not difficult however to extract those subroutines relevant to the free-field only for use of FRAM with other codes. The subroutines interacting with SAP are READIT, EMPIR, RESTWR.

2.2.1 FRAM.

The main program calls READIT where some of the parameters are defined and the coordinates of the point of observation are provided by SAP. NWET is the number of wet nodes, KTIM is the number of time history points. The explosion's parameters are obtained in part from empirical data in EMPIR. CAVITY is called for each point of observation and ECHO is called for each time step. The output is written for SAP in RESTWR.

Although running the code does not require a complete understanding of the theory, references to equations and figures in ref.[1] have been included for the sake of completeness. The correspondence between some of the symbols in ref. [1] and in FRAM is as follows:

$CC=c$, $PS=p_s$, $L=L$, $PA=p_A$, $GAM=\gamma_0$, $GV=g$, $T=\theta$, $TT=\beta$, $AA=\alpha$, $AL=\alpha l$, $YB=y_B$, $SB=\xi_B$, $YC=y_C$, $SC=\xi_C$, $YA=y_A$, $SA=\xi_A$, $FH=\frac{g}{c^2}$, $F=\frac{2p_s}{\rho a^2}$, $XI(1)=\chi_B$, $XI(2)=\chi_A$, $R=R$, $E=\Delta\xi$, $A=A$, $AH=f_U$, $GR=g_T$, $ST=\xi$, $HS=\Delta\xi$, $YX=y$, $PRE=\rho$, $VEL=m$, $UEL=n$, $F=F$, $G=G$.

2.2.2 CAVITY.

In the following, references to equations and figures found in ref.[1] will appear in parentheses. This subroutine starts by defining some parameters in order to use a non-dimensional formulation. The coordinates of point B are given by finding the first point on the opening interface AB where the density has a change in sign due to closing of the cavity (eq (39)). The coordinates of point A are found on AB where the pressure first drops to zero (eq(51)) using subroutine NEWTON. The slopes of AC and BC at points A and B are also evaluated using Taylor series expansions (eqs(90) and(83)).

Next, curves AB and BC are constructed incrementally, with an increment size E which is determined such that ξ_B coincides with the ξ value of one of the discrete points of curve AC. The curves AC and BC are constructed one point at a time. Starting from the coordinates of a point I and the slope at that point, one can determine the coordinates of the next point, I+1 and the slope of the next increment by a first order linear approximation.

The array D(I,J) contains the properties of the curve's discrete points. J=1 corresponds to curve BC or lower curve and J=2 to curve AC or upper curve. I is the index of the discrete points; there are KK more points on AC than on BC. D(I,1) is the characteristic f_I (eq(97)), D(I,2) is the characteristic g_I (eq(99)).

Additional arrays which do not appear in ref. [1] are $M(I)$ and $P(I)$. These represent $M = -y + \theta\xi$, $P = y + \theta\xi$ and are used to determine the location of the point of observation with respect to the cavity, i.e. between which of the discrete points of the cavity the characteristic functions defining the properties of the point of interest fall.

S is augmented at each step by an increment and $Y(I)$ is the result of the previous cycle of computations (eq(69)). For the upper curve, the characteristic emanating from I is reflected on the free surface at U and intersects the y axis at T or the curve AC itself at R see (fig.(8) in ref[1]). For the lower curve, R is defined as the intersection of the characteristic emanating from point I and the y axis (fig.(7.a) in ref[1]).

The upper curve is constructed first, it is more complex than the lower one since the characteristics are reflected on the free surface and fall back on the portion of the curve freshly constructed at point R . The properties at point $I+1$ are deduced from those at point I using conservation equations and geometry (eqs(69) and (71)) in which the expressions for f_U, g_W, g'_W are needed. If R falls on the y axis, then it corresponds to point T in fig.(7.c) of ref. [1], f_U is determined from geometrical relations (eq(73)). If R falls on the beginning of AC , then an interpolation between the two adjacent points is required to evaluate f_U . The remaining two terms, g_W, g'_W are simply found by calling the functions g, g' with the argument y_W . g is given by its definition (eqs(27), (33), and (34) for a point on the y axis).

The construction of the lower curve requires the evaluation of a similar equation expressing the conservation laws and geometrical relations (eq(68)), and in particular g_W, g'_W, g_T which is simply done by calling the functions.

This procedure is repeated until the two curves intersect at point C .

2.2.3 ECHO.

In order to obtain p, m at y, ξ it is sufficient to know f, g (eqs.(102), (103)). Using geometry and characteristic relations, the characteristics at X are expressed in terms of similar characteristics at points where these are known. Fig.(8) in ref[1] shows the possible zones in which the point may fall. A zone is the ensemble of points with same expressions for the generalized Riemann invariants (Table.1). ECHO calls ZONE where the zone number is found and pressure and velocity are computed accordingly. Results are converted in dimensional quantities and stored in $O(NT, J)$ for plotting.

2.2.4 ZONE.

Z is the zone number, F and G are defined in Table 1.. The coordinates of the points defined in Table 2. are computed first. Then a test is performed to determine whether X belongs to a given zone. F and G are assigned appropriate values which allows the computation of p, m . In some cases it is necessary to call SEARCH to locate X .

2.2.5 SEARCH.

Using the arrays P , and M created in CAVITY this routine finds between which points of AC or BC the characteristics emanating from X falls. HFG is either F or G . When X

falls in 5 or 7, then a linear interpolation between adjacent discrete points of the boundaries is performed.

SECTION 3

EXAMPLE

Examples of output are presented in the following figures. An example of the cavitated region is shown in Fig.1.

The location of the charge relative to the submerged surface of the ship and origin of SAP coordinates appear in Fig.2. The free-field values for the submerged nodes 8, 18, and 28 which are specified within SAP as nodes 33, 43, and 53 appear in Fig.3.

Fig.3 shows in (a) the free-field pressure which is characterized by a pressure pulse followed by a surface relief effect (pressure drop below zero line) and terminated by a secondary pulse due to the closure of the cavitated region. The integral of the pressure is the impulse which is plotted in (b). One can follow in (c) the correlation between vertical free-field velocities and pressures of (a). The initial upward velocity is due to the first spike in (a). A free fall under gravity inside the cavitated region follows and is terminated due to the increase in pressure resulting from the cavitation closure (second spike in (a)). These free-field velocities are integrated to give displacements shown in (d).

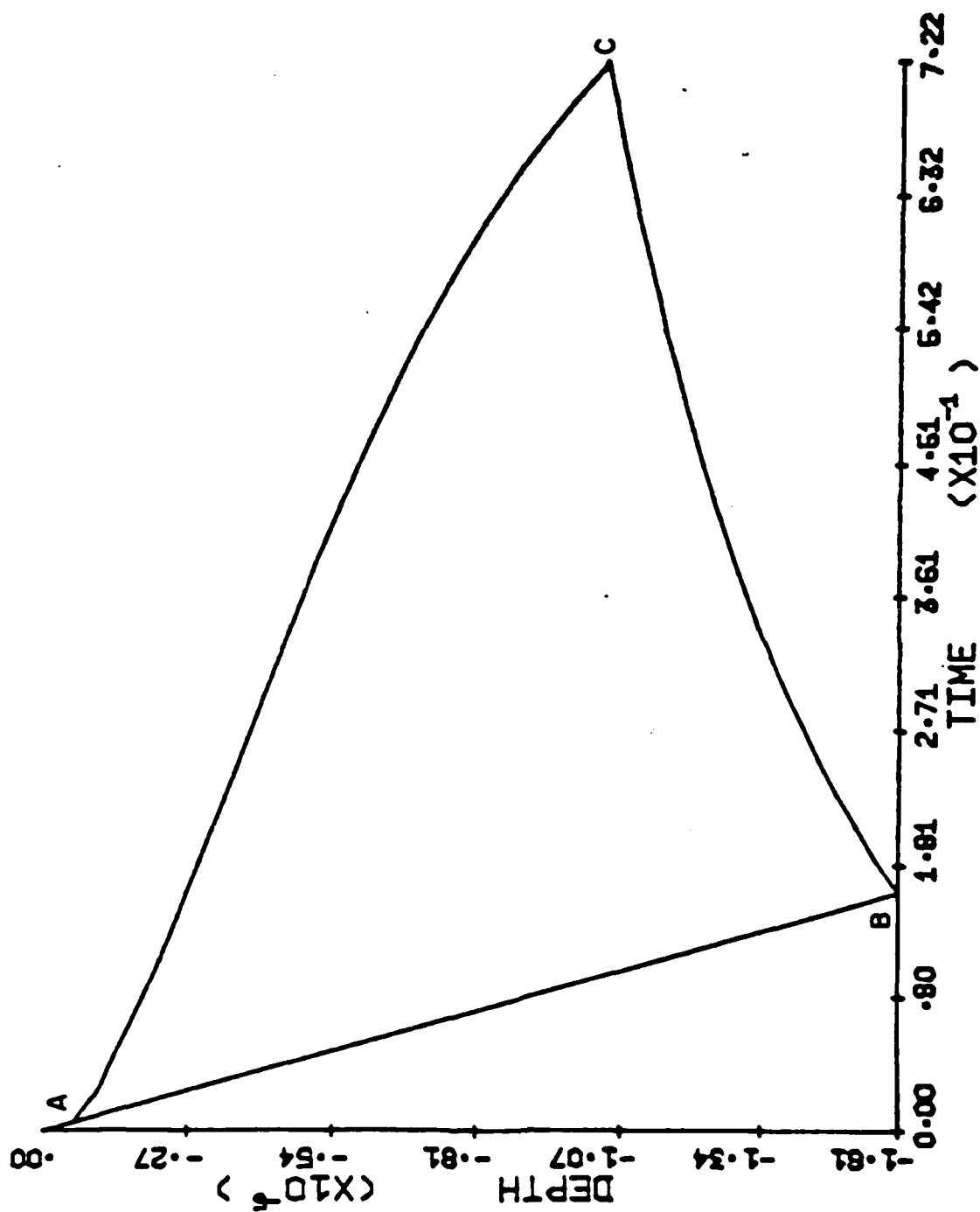


Figure 1. Cavitated region non-dimensional units.

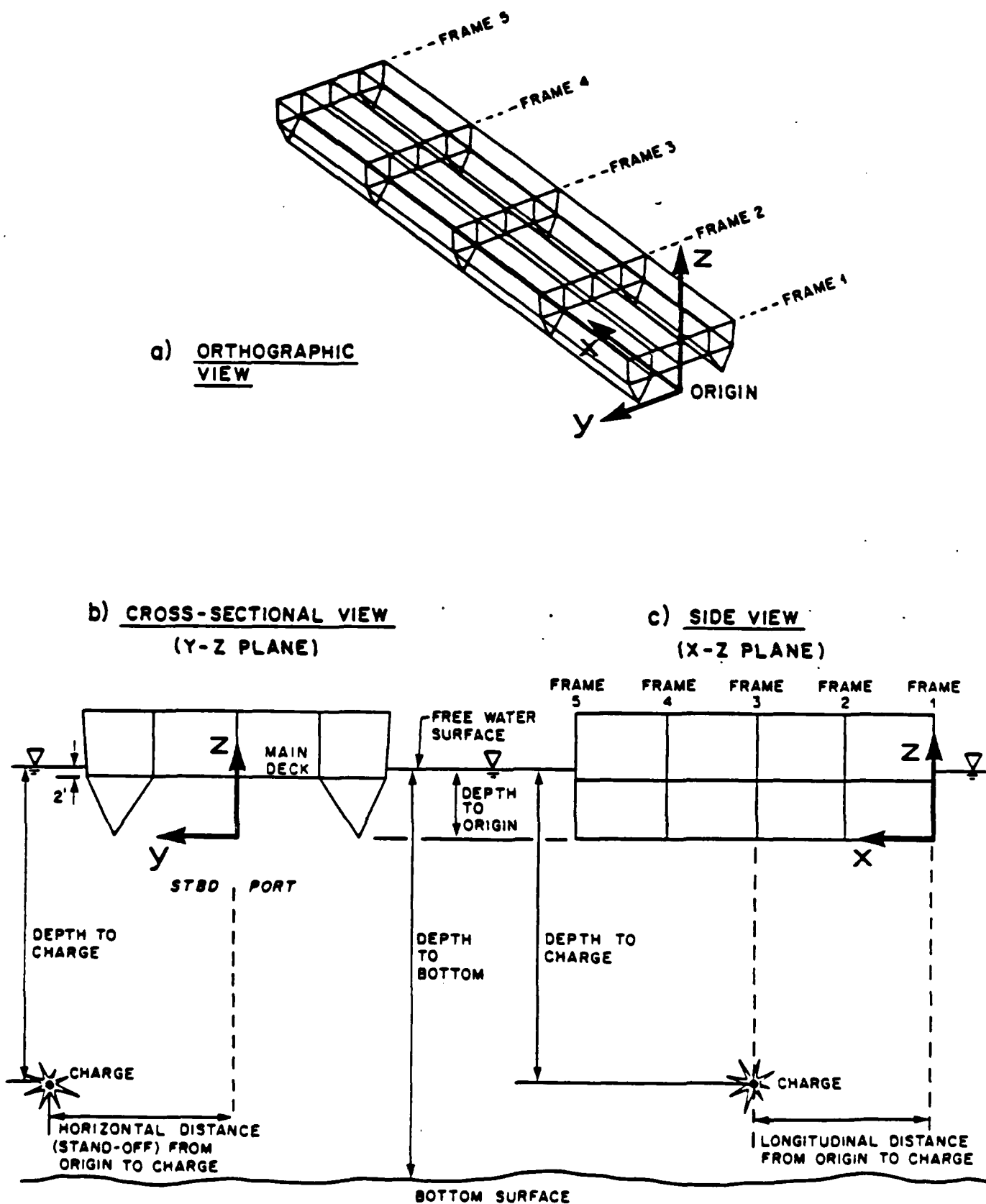
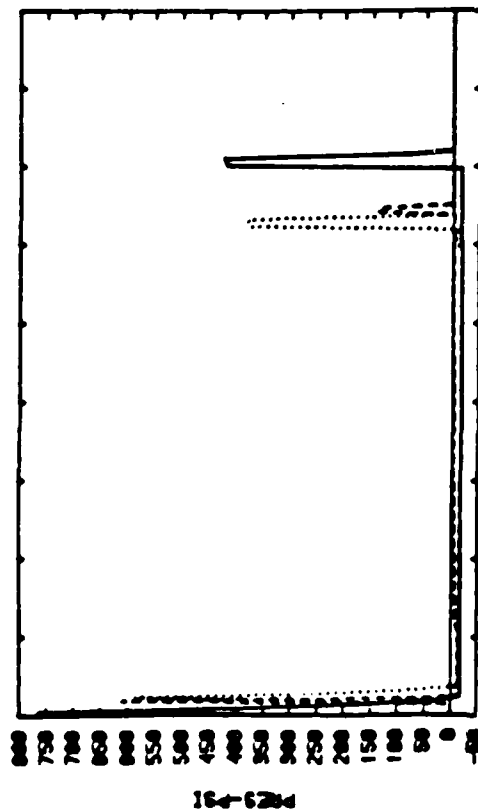
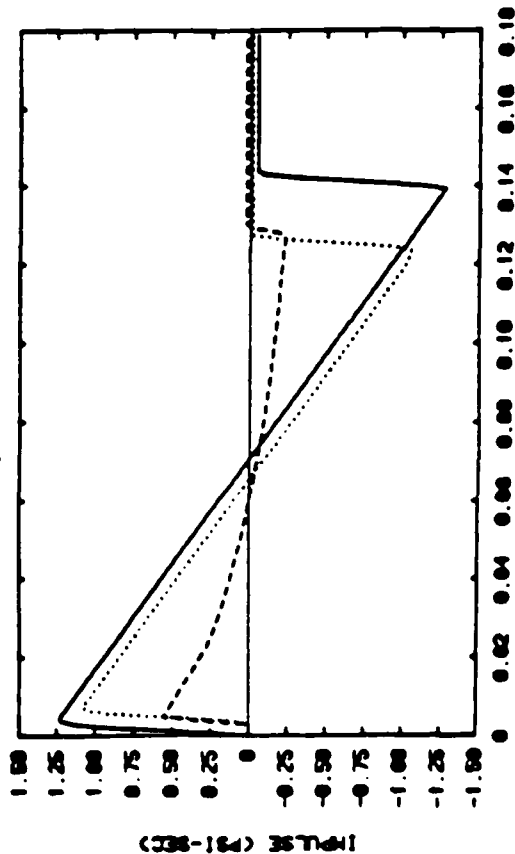


Figure 2. Global coordinate system and orientation of surface ship to underwater explosion for sample problem.

——— EXPROB/FF/UTEDB/R~ 04.5, Z~ 0.2 MET NODE 8 (LAB 33)
 - - - EXPROB/FF/UTEDB/R~ 00.0, Z~ 2.0 MET NODE 18 (LAB 43)
 EXPROB/FF/UTEDB/R~ 05.5, Z~ 0.2 MET NODE 28 (LAB 53)

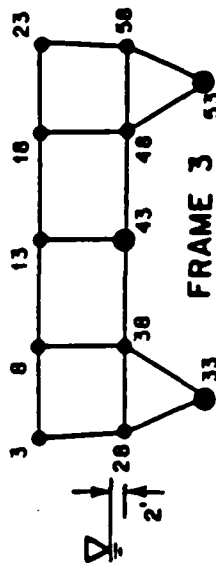


(a) Free-field pressures

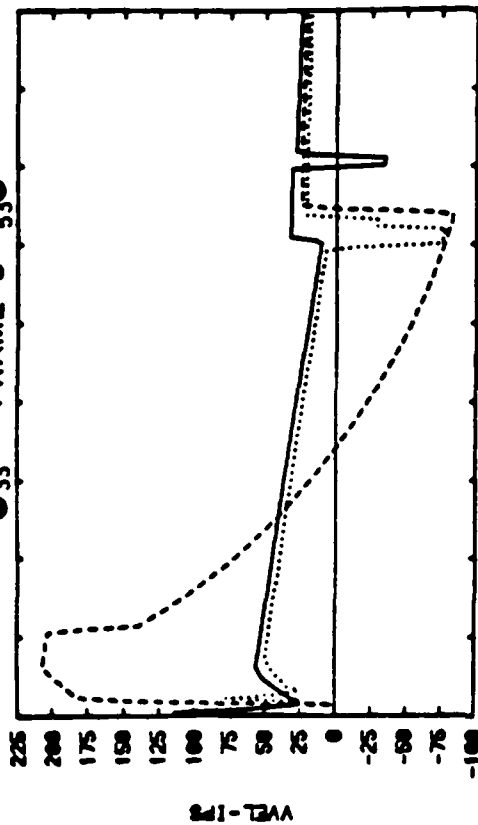


(b) Free-field impulses

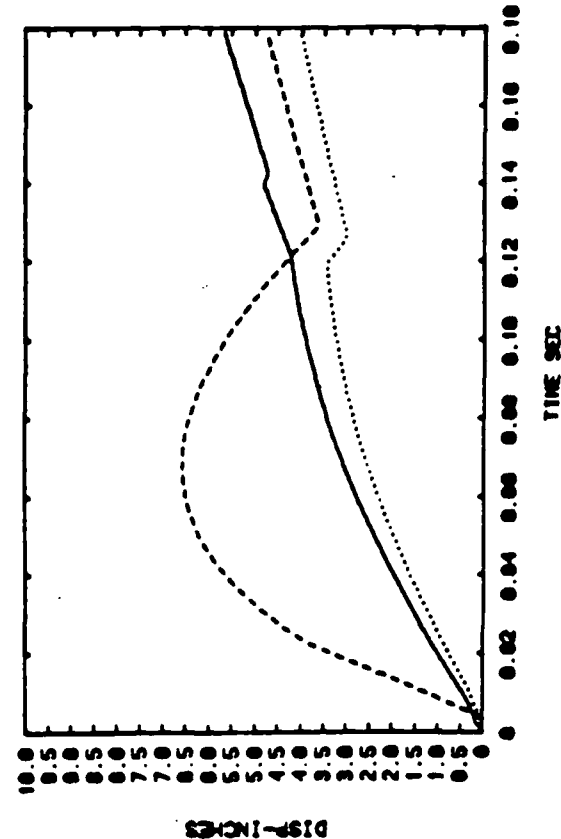
Figure 3. Free-field pressure (a), free-field impulse (b), free-field velocity (c) and free-field displacement (d) for wet nodes 8, 18 and 28 on frame 3.



FRAME 3



(c) Free-field velocities



(d) Free-field displacement

SECTION 4
SOURCE CODE

```

PROGRAM FRAM (INPUT, OUTPUT, TAPE5=INPUT, TAPE6=OUTPUT
* TAPE9, TAPE14, TAPE99)
COMMON/CUE/M, DO, H, IBOT, NWET, ZSURF, SSS
COMMON/DAT/PPS, XLE, PS, PA, L, TT, GV, CC, GAM
COMMON/CONS/T, E, AA, AL, N1, N2, KK, XS(2)
COMMON/DAWGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000, 2), XI(2)
COMMON/AHEAD/D(25000, 2), NPTS, INOW, NNOW, ISKIP
COMMON/POINTS/YA, SA, YB, SB, YC, SC
COMMON/GRID/YXO, SXO, FX, HS, KTIM, R11, R1, SQ
COMMON/CUMBER/YLABEL(3), YMIN(3), YMAX(3), TITLE(10)
COMMON/KE/RHIS(1000), ZHIS(1000), MIN, RMIN, DT, PEDFAC
COMMON/MIO/ST(15000), O(15000, 3)
REAL L, M
CALL READIT
DO 2 MN=1, NWET
CALL EMPIR(MN)
GENERATE THE CAVITY'S BOUNDARY
CALL CAVITY
DO 1 NT=1, KTIM
CALL ECHO(NT, MN)
CONTINUE
CALL RESTWR(MN)
CONTINUE
REWIND 99
STOP
END
SUBROUTINE READIT
COMMON/CUE/M, DO, H, IBOT, NWET, ZSURF, SSS
COMMON/DAT/PPS, XLE, PS, PA, L, TT, GV, CC, GAM
COMMON/CONS/T, E, AA, AL, N1, N2, KK, XS(2)
COMMON/DAWGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000, 2), XI(2)
COMMON/AHEAD/D(25000, 2), NPTS, INOW, NNOW, ISKIP
COMMON/POINTS/YA, SA, YB, SB, YC, SC
COMMON/GRID/YXO, SXO, FX, HS, KTIM, R11, R1, SQ
COMMON/CUMBER/YLABEL(3), YMIN(3), YMAX(3), TITLE(10)
COMMON/KE/RHIS(1000), ZHIS(1000), MIN, RMIN, DT, PEDFAC
COMMON/MIO/ST(15000), O(15000, 3)
REAL L, M
GRAV=0.000322
GAM=1.94
CC=5236.
GV=32.2
RHO=62.4/144./GRAV
PEDFAC=RHO*CC*SQRT(8.)
RMIN=1.E9
RMAX=0.
MIN=1
FH=GV/CC**2
WRITE(6,75)CC, GV, FH
FORMAT(' CC, GV, FH', 3E10.3)
REWIND 14
READ(14)W, DO, H, IBOT, NWET, ZSURF, XXI, SSS, DT
IF(DT.LT.0.01) DT = DT*1000.
REWIND 9

```

```

11 WRITE(6,11)
   FORMAT(' W,D,M,IBOT,NMET,ZSURF,XI,SSS,KTIM,DT',/)
9   WRITE(6,9)W,D,M,IBOT,NMET,ZSURF,XI,SSS,KTIM,DT,FH
   FORMAT(3F10.3,2I5,3F10.3,15,2E10.3)
   WRITE(9) W,D,M,IBOT,NMET,ZSURF,XI,SSS,DT,KTIM
   ENCODE(48,999,TITLE)W,DO,XI/12.0,-SSS/12.0
999 FORMAT(4H W-,F8.0,7H DEPTH-,F8.1,4H XI-,F8.1,7H STAND-,F8.1)
   XXI = -XXI
   CALL REMARK(TITLE)
   DO 10 I=1,NMET
   READ(14)IDUM,XSAP,YSAP,ZSAP
   WRITE(6,78)XSAP,YSAP,ZSAP
78  FORMAT(' X,Y,Z',3E10.3)
   RHIS(1)=(SORT((XSAP+XXI)*2+(YSAP+SSS)*2))/12.
   ZHIS(1)=AMAX1(0, (ZSURF-ZSAP)/12.)
   WRITE(6,77)RHIS(1),ZHIS(1)
77  FORMAT(' R Z',2E10.3)
   WRITE(9)IDUM,XSAP,YSAP,ZSAP
10  CONTINUE
   CALL DATE(TITLE(9))
   CALL CLOCK(TITLE(10))
   R1=1.E100
   RMAX=R1
   DO 100 MN=1,NMET
   ER= SORT(RHIS(MN))*2+(DO-ZHIS(MN))*2)
   IF(ER.LE.RMAX) GO TO 99
   RMAX = ER
   MAX = MN
99  CONTINUE
   IF(ER.GT.R1)GO TO 100
   R1=ER
   MIN=MN
100 CONTINUE
   TOTIME = AMAX1(1000.0*(2.0*RMAX-R1)/CC,100.0)
   ET=1.E100
   DO 200 MN=1,NMET
   T=RHIS(MN)/(DO-ZHIS(MN))
   TT=ATAN(T)
   YT=ZHIS(MN)/T
   IF(YT.GT.ET)GO TO 200
   ET=YT
   MINT=MN
200 CONTINUE
   CALL EPIR(MINT)
   HS = ET*FH/4.
   HRS=FH*LSIN(TT)/10.
   IF(HRS.LT.HS)HS=HRS
   KTIM = 1+(DT*GV)/(HS*1000.0*CC)
   ISKIP = MAX0(((KTIM-12)/8)+1,1)
   KTIM = ((KTIM-1)/ISKIP+1)*ISKIP
   HS = (DT*GV)/(KTIM*1000.0*CC)
   KTIM = (KTIM*TOTIME)/DT
   WRITE(6,87)MIN
   FORMAT(' MINIMUM',15)
   R11= SORT(RHIS(MIN))*2+(DO-ZHIS(MIN))*2)
   R1=(10+ISKIP)*HS*CC*CC/GV
   CALL CUEINIT(ET)
   RETURN
   END
   SUBROUTINE CUEINIT(ET)

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```

COMMON/CUE/W,DD,M,IBOT,NWET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DANGER/P(25000)
COMMON/ECUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FXO,HS,KTIM,R11,R1,SQ
COMMON/CLMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/XE/RHIS(1000),ZHS(1000),MIN,RMIN,DT,PEDFAC
COMMON/MTO/ST(15000),O(15000,3)
1JDIM=225000
RMIN = 1.E9
RMAX = -RMIN
DO 1 MH=1,NWET
  RMAX = AMAX1(RMAX,RHIS(MH))
  RMIN = AMIN1(RMIN,RHIS(MH))
CONTINUE
BRITE = 1.2*RMAX
IARG = SORT(IJDIM+H/BRITE*2.)
JDIM = MAX0(IARG,5)/2*2-1
IDIM = 1JDIM/(JDIM+1)
DR = H/(JDIM - 4)
C = CC*0.001
N = IFIX(DT*C/(DR*SORT(2.0)))
IF(N.EQ.0) GO TO 20
DR = DT*C/(N*SORT(2.0))
HBAR = (JDIM-4)*DR
IF(ABS(HBAR-H).LT.DR) GO TO 20
JDIM = JDIM - 2
GO TO 10
NTIME = IDIM/6*12
RCAV = AMIN1(DD,M-DD)-DR
DELT = SORT(2.)*DR/C
ITHIS = (RMIN-RCAV)/C/DELT - 1
NPRIN = MAX0(1THIS,0)/6*6
NTIME = NTIME - NPRIN
NT = 2*NTIME
DELT = DELT*.5
HS = ET*FH/4.
HHS = FH*L*SIN(TT)/10.
IF(HHS.LT.HS) HS=HHS
ISKIP = 1+(DELT*GV)/(HS*1000.*CC)
HS = (DELT*GV)/(ISKIP*1000.*CC)
KTIM = ISKIP*NT
T1ST = RCAV/C + NPRIN*DELT*2.
R1 = R11 - T1ST*C
RETURN
END
SUBROUTINE EMPIR(MN)
COMMON/CUE/W,DD,M,IBOT,NWET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DANGER/P(25000)
COMMON/ECUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FXO,HS,KTIM,R11,R1,SQ

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COMMON/CLMBER/ LABEL(3), YMIN(3), YMAX(3), TITLE(10)
COMMON/KE/RHIS(1000), ZHIS(1000), MIN, RMIN, DT, PEDFAC
COMMON/MIO/ST(15000), O(15000, 3)
REAL L, M
R = SORT(RHIS(MN))**2+(DO-ZHIS(MN))**2)
WJR=0.0/(1./3.)/R
PA=14.7
PS=22347.6*WJR**1.144
L=6.056*R*WJR**0.753
IF(L.EQ.0.0) L=10.
L=L*CC/1000
T=RHIS(MN)/(DO-ZHIS(MN))
TT=ATAN(T)
PPS=PS
XLE=L
WRITE(6,1)PS,L,T,TT
FORMAT(' PS,L,TAN(THET),THET',/4E10.3)
INOW = 1
RETURN
END
SUBROUTINE CAVITY
COMMON/CUE/M,DO,H,IBOT,MNET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,MK,XS(2)
COMMON/DANGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/ANHEAD/D(25000,2),NPTS,INOW,MNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FH,HS,KTIM,R11,R1,SQ
COMMON/CLMBER/ LABEL(3), YMIN(3), YMAX(3), TITLE(10)
COMMON/KE/RHIS(1000), ZHIS(1000), MIN, RMIN, DT, PEDFAC
COMMON/MIO/ST(15000), O(15000, 3)
REAL L, M
INTEGER Z
PS=PS*144./((GAM*CC**2)
PA=PA*144./((GAM*CC**2)
AA=1./COS(TT)
AL=AA*L*FH
J=1)FOR LOWER CURVE, J=2 FOR UPPER ONE
FIND POINT B AND INITIAL SLOPE
F=2.*PS/AL
YB=(AL/2.)*ALOG(F)
YB=TO/2.2
Y(1,1)=YB
SB=YB/T
XI(1)=T/5.
FIND POINT A AND INITIAL SLOPE
CALL NEWTON6 TO SOLVE Y=F(Y)
CALL NEWTON
Y(1,2)=YA
SA=YA/T
R=(F*EXP(-2.*YA/AL)-1.)/(F-1.)
XI(2) =T/(1.+4.*R)
FIND CLOSURE CURVES
GENERATE THE COORDINATES

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15

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40 IF(N.EQ.1) GO TO 40
   GR-D(N,2)+(D(N+1,2)-D(N,2))*ZMN
   CONTINUE
   IF(N.NE.1) GO TO 20
   N IS EQUAL TO I
C-----
   B=Y(N,2)-X*(S-E)
   YRR=(X*YRR+T*B)/(X+T)
   GR=G(2,*YRR)
   DO 41 IK=1,IMAX
   AH=GR+2.*PA
   A=IFAC*2.*GG(YW)*YR/(G(Y)-AH)
   D(I+1,J)=(A*AH+2.*G(YW))/(A+2.)
   GR=GR
   GR-D(N,2)+(D(N+1,2)-D(N,2))*ZMN
   GRN=GR
   DIFF=GRN-GR
   IF(ABS(DIFF).LT.0.0000000001)GO TO 101
   IF(IK.EQ.IMAX)WRITE(6,2)
   FORMAT(/," N2=",I3," J=",I3," IK=",I3,"DIFF=",E20.8)
   CONTINUE
   CONTINUE
   WRITE(6,100)N2,J,IK,DIFF
   FORMAT(/," N2=",I3," J=",I3," IK=",I3,"DIFF=",E20.8)
   AH=GR+2.*PA
   COMPUTE THE SLOPE
   A=IFAC*2.*GG(YW)*YR/(G(YW)-AH)
   XI(J)=T/(1.+A)
   STORE PROPERTIES
   WHEN J=2,D=G
   WHEN J=1,D=F
   D(I+1,J)=(A*AH+2.*G(YW))/(A+2.)
   IF(DEL.LT.0.)GO TO 10
   CONTINUE
5 C-----
C+++++
C.....
   WRITE(6,19)
   FORMAT(/," CLOSURE NOT REACHED.RUN TERMINATED.")
   N1=N2-KK
   WRITE(6,75)
   FORMAT(/," I Y1 Y2")
   WRITE(6,85)(I,Y(I,1),Y(I,2),I=1,N2)
   FORMAT(15,2E20.8)
   STOP
   CONTINUE
10 N2 IS THE NUMBER OF TIME STEPS ON UPPER CURVE(PASSING C)
C-----
C.....
   N1=N2-KK
   WRITE(6,9999)I,N2,KK
   FORMAT(10H I,N2,KK .3I10)
   COMPUTE COORDINATES OF CLOSURE POINT C
   YC=(Y(N2,2)*XI(1)+Y(N1,1)*XI(2))/(-XI(1)+XI(2))
   SC=(N2-1)*E-(Y(N2,2)-YC)/XI(2)+SA
   RETURN
   END
SUBROUTINE NEWTON
COMMON/CUE/M,DO,H,IBOT,NWET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)

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COMMON/DANGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FH,HS,KTIM,R11,R1,SQ
COMMON/CUMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/KE/RHIS(1600),ZHS(1600),MIN,RMIN,DT,PEDFAC
COMMON/MIO/ST(15000),O(15000,3)
R=1
F=2, *PS/AL
YA=PA/(F-1.)
KAM=100
DO 2 I=1,KAM
IF (ABS(R).LT..00000001) GO TO 1
PE=PA-PS+YA+PS*EXP(-2.*YA/AL)
PP=1.-F*EXP(-2.*YA/AL)
R=PE/PP
YA=YA-R
CONTINUE
WRITE(6,4)I
FORMAT(1H," FAILURE TO SOLVE EQU. IN # OF STEPS =",I4,/)
CONTINUE
RETURN
END
2
4
1
FUNCTION G(WY)
COMMON/CUE/W,DO,H,IBOT,NMET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DANGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FH,HS,KTIM,R11,R1,SQ
COMMON/CUMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/KE/RHIS(1600),ZHS(1600),MIN,RMIN,DT,PEDFAC
COMMON/MIO/ST(15000),O(15000,3)
EXPZ(Z)=EXP(AMAX1(-500.,Z))
G=-2.*PS*(EXPZ(-WY/AL))-WY -PA
RETURN
END
FUNCTION GG(WY)
COMMON/CUE/W,DO,H,IBOT,NMET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DANGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FH,HS,KTIM,R11,R1,SQ
COMMON/CUMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/KE/RHIS(1600),ZHS(1600),MIN,RMIN,DT,PEDFAC
COMMON/MIO/ST(15000),O(15000,3)
EXPZ(Z)=EXP(AMAX1(-500.,Z))
GG=-1.+2.*PS*(EXPZ(-WY/AL))/AL
RETURN
END
SUBROUTINE ZONE(Z,YX,SX,PRE,VEL,NT)

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COMMON/CUE/W,DD,H,IBOT,NMET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,CV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DANGER/P(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FXO,HS,KTIM,R11,R1,SQ
COMMON/CUMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/NE/RHIS(1000),ZHS(1000),MIN,RMIN,DT,PEDFAC
COMMON/MTO/ST(15000),O(15000,3)
REAL L,M
INTEGER Z
YXR=YX+T*SX
YXT=YX+T*SX
YCT=YC+T*SC
YCR=YC+T*SC
YAT=YA+T*SA
YAR=YA+T*SA
Z=8
F=PA-YXR
C=PA-YXT
IF(YXT.LT.O.) GO TO 1
Z=1
C=G(YXT)
IF(YXR.LT.O.) GO TO 1
Z=2
F=G(YXR)+2.*PA
IF(YXT.LE.YAT) GO TO 1
Z=2
IF(YXR.GE.YCT) GO TO 1
Z=3
IF(YXR.LT.YCR.OR.YXT.LT.YCT) GO TO 44
CALL SEARCH(-1.,1.,F,YX,SX)
F=F+2.*PA
GO TO 1
IF(SX.GE.SC.AND.YX.GT.YC) GO TO 444
IF(SX.GE.SC.AND.YX.LE.YC) GO TO 6
Z=4
DO 20 JJ=1,2
IF(JJ.EQ.0000001) XS(1)=2.*YX
IF(JJ.EQ.1.AND.SX.LT.SB) GO TO 20
N=1+(SX-SA+E*KK*(JJ-2))/E
SN=SA+E*(KK*(2-JJ)+N-1)
XS(JJ)=(Y(NH1,JJ)-Y(N,JJ))/E
XS(JJ)=XS(JJ)*(SX-SN)+Y(N,JJ)
CONTINUE
IF(YX.LE.XS(1)) GO TO 5
CALL SEARCH(-1.,-1.,F,YX,SX)
GO TO 1
Z=5
IF(YX.LT.XS(2)) GO TO 6
C=2.*GG(2.*YX)*(SX*SIN(TT)/AA-YX/AA**2)
F=C+G(2.*YX)
C=C+G(2.*YX)
GO TO 1
Z=6
CALL SEARCH(1.,1.,C,YX,SX)
IF(YXR.LT.YAT) GO TO 7

```

2

44

20

444

5

6

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CALL SEARCH(-1,1,1..F.YX,SX)
INOW=MAX0(NNOW,INOW)
F=F+2.*PA
GO TO 1
Z=7
F=G(YXR)+2.*PA
CONSTRUCT VELOCITY AND PRESSURE ARRAY
CONTINUE
VEL=((F+C)/(2.*AA))+SX*SIN(TT)+HS*(NT-1)
PRE=(F-C)/2.
RETURN
END
SUBROUTINE SEARCH(B,C,HFG,YX,SX)
COMMON/CUE/N,DD,H,IBOT,NWET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DAANGER/P(25000)
COMMON/EOUS/N(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FH,HS,KTIM,R11,R1,SQ
COMMON/CUMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/KE/RHIS(1600),ZHIS(1600),MIN,RMIN,DT,PEDFAC
COMMON/MIO/ST(15000),O(15000,3)
REAL L,M
RT=B*YX+T*SX
J=2
IF(C.LT.0)J=1
DO 1 I=INOW,NPTS
IF(C.GT.0..AND.B*YX+T*SX.LT.P(I)) GO TO 10
IF(C.LT.0..AND.B*YX+T*SX.LT.M(I)) GO TO 10
CONTINUE
N=I-1
X=(Y(N+1,J)-Y(N,J))/E
SX=SA+(N-I+(2-J)*KK)*E
XX=(B+C*YX-Y(N,J)+T*C*(SX-SN))/((T+C*X)*E)
HFG=D(N,J)*(1.-XX)+D(N+1,J)*XX
NNOW=N
RETURN
END
SUBROUTINE ECHO(NT,MN)
COMMON/CUE/N,DD,H,IBOT,NWET,ZSURF,SSS
COMMON/DAT/PPS,XLE,PS,PA,L,TT,GV,CC,GAM
COMMON/CONS/T,E,AA,AL,N1,N2,KK,XS(2)
COMMON/DAANGER/P(25000)
COMMON/EOUS/N(25000)
COMMON/CURVE/Y(25000,2),XI(2)
COMMON/AHEAD/D(25000,2),NPTS,INOW,NNOW,ISKIP
COMMON/POINTS/YA,SA,YB,SB,YC,SC
COMMON/GRID/YXO,SXO,FH,HS,KTIM,R11,R1,SQ
COMMON/CUMBER/YLABEL(3),YMIN(3),YMAX(3),TITLE(10)
COMMON/KE/RHIS(1600),ZHIS(1600),MIN,RMIN,DT,PEDFAC
COMMON/MIO/ST(15000),O(15000,3)
INTEGER Z
ST(NT)=(NT-1)*HS
YX=ZHIS(MN)*FH
R = SORT(RHIS(MN))**2+(DD-ZHIS(MN))**2
SX=YX/T+(HS*(NT-1)-(R-R11)*FH)/SIN(TT)

```

7

C

1

10

C

1

10

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16 SX = SX - R1*FH/SIN(TT)
   IF (NT.GE.2) GO TO 22
   WRITE(6,16) MN, YA, SA, YB, SB, YC, SC
   FORMAT(6H NODE=, I5, 20H YA, SA, YB, SB, YC, SC /6E10.3)
   YXX=YX/T
   WRITE(6,17) FH, HS, YX, SX, YXX
   FORMAT(12H FH=, E10.3, 12H HS=, E10.3, 12H YX=, E10.3, 12H SX=, E10.3
   , 12H YXX=, E10.3)
22 CONTINUE
   CALL ZONE (Z, YX, SX, PRE, VEL, NT)
   VEL=VEL+(NT-1)*HS
   UEL=(-AMAX1(0., PRE)+PA+YX)*SIN(TT)
   O(NT,1)=AMAX1(PRE, 0.)
   O(NT,2)=UEL
   O(NT,3)=VEL
   WRITE(6,8) NT, Z, PRE, UEL, VEL
   FORMAT(15, I3, 4E10.3)
   ST(NT)=1000.*ST(NT)*CC/GV
   O(NT,1)=O(NT,1)-PA-YX*CC+CC**2/144.
   O(NT,2)=O(NT,2)*CC
   O(NT,3)=O(NT,3)*CC
   RETURN
   END
SUBROUTINE RESTWR(MN)
COMMON/CUE/M, DO, H, IBOT, NWET, ZSURF, SSS
COMMON/DAT/PPS, XLE, PS, PA, L, TT, GV, CC, GAM
COMMON/CONS/T, E, AA, AL, N1, N2, KK, XS(2)
COMMON/DAWG/R(25000)
COMMON/EQUS/M(25000)
COMMON/CURVE/Y(25000,2), X1(2)
COMMON/AHEAD/D(25000,2), NPTS, INOW, NNOW, ISKIP
COMMON/POINTS/YA, SA, YB, SB, YC, SC
COMMON/GRID/YXO, SXO, FH, HS, KTIM, R11, R1, SO
COMMON/CUMBER/LABEL(3), YMIN(3), YMAX(3), TITLE(10)
COMMON/KE/RHIS(1600), ZHIS(1600), MIN, RMIN, DT, PEDFAC
COMMON/MIO/ST(15000), O(15000,3)
DIMENSION TL(20)
REAL L, M
REAL MVC
DATA TPC, APC, VTC, MVC, FOURPI/4970., 33., 3.21, 12414., 12.5663706/
HH(1)=AMAX1(0., AMIN1(T/TP, 1.-T/TP, .01))*100.
VDOTR(T)=VTC/TP*(VMAX*(COS(VTC*T/TP))*HH(T))
TP=TPC*W**((1./3.)/(DD+APC)**(5./6.))
VMAX=MVC*W/(DD+APC)
KTEMP = KTIM
KTIM = KTIM/ISKIP
IF (MN.GT.1) GO TO 33
NH=3*NWET
DECODE(80, 98, TITLE) TL
FORMAT(20A4)
WRITE(9) TL, KTIM, NH
IFIVE=5
IEIGHT=8
TLABEL=8HT (MSEC)
DO 15 I=1, KTIM
ST(I) = ST(1)*ISKIP
DT =ST(2) - ST(1)
WRITE(9) IFIVE*KTIM, TLABEL, ST(1), ST(KTIM), (ST(I), I=1, KTIM)
WRITE(6,17)
FORMAT(12H 5, KTIM, TLABEL, ST(1), ST(KTIM))

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C 7 WRITE(6,7)IFIVE,KTIM,TLABEL,ST(1),ST(KTIM)
  FORMAT(214,A8,2E10,3,/,)
  YLABEL(1)=BPPR(PST)
  YLABEL(2)=BPPV(FT/S)
  YLABEL(3)=BPPV(FT/S)
  CONTINUE
33 SMALL=1.E-50*CC
  YMIN(1)=SMALL*PEDFAC
  YMAX(1)=SMALL*PEDFAC
  YMIN(2)=SMALL
  YMAX(2)=SMALL
  YMIN(3)=SMALL
  YMAX(3)=SMALL
  BICR=SQRT(RHIS(MN))*2+(DO-ZHIS(MN))*2
  BICR1=SQRT(RHIS(MN))*2+(DO+ZHIS(MN))*2
  TZERO = (R11-R1)/CC*1000.
  DO 350 I=1,KTIM
    T=ST(1)+TZERO
    TAU=T-(BICR/CC)*1000.
    TAUI=T-(BICR1/CC)*1000.
    USUBV=1./FOURPI*((DO+ZHIS(MN))/(BICR1*3)+VDOTR(TAU1))
    C USUBH=RHIS(MN)/FOURPI*((1./BICR*3)+VDOTR(TAU))
    C -((1./BICR1*3)+VDOTR(TAU1))
    PPP=0
    UUU=0.
    VVV=0.
    DO 300 J=1,ISKIP
      PPP = PPP + 0*((1-1)*ISKIP+J,1)/ISKIP
      UUU = UUU + 0*((1-1)*ISKIP+J,2)/ISKIP
      VVV = VVV + 0*((1-1)*ISKIP+J,3)/ISKIP
    CONTINUE
300 O(1,1) = PPP
    O(1,2) = -UUU*USUBH*1000.
    O(1,3) = VVV*USUBV*1000.
    YMAX(1)=AMAX1(YMAX(1),PPP)
    YMIN(1)=AMIN1(YMIN(1),PPP)
    YMAX(2)=AMAX1(YMAX(2),UUU)
    YMIN(2)=AMIN1(YMIN(2),UUU)
    YMAX(3)=AMAX1(YMAX(3),VVV)
    YMIN(3)=AMIN1(YMIN(3),VVV)
  CONTINUE
350 DO 400 I=1,3
    WRITE(9)IEIGHT,KTIM,YLABEL(1),RHIS(MN),ZHIS(MN)
    *DT,YMIN(1),YMAX(1),O(K,1),K=1,KTIM
    WRITE(6,10)
10  FORMAT(' 8 ,KTIM,YLABEL,RHIS,ZHIS,DT,YMIN,YMAX')
    WRITE(6,6)IEIGHT,KTIM,YLABEL(1),RHIS(MN),ZHIS(MN)
    *DT,YMIN(1),YMAX(1),O(K,1),K=1,10
    *DT,YMIN(1),YMAX(1),O(K,1),K=1,10
6  FORMAT(214,A8,5E10,3,/,10E10,3)
400 CONTINUE
    KTIM = KTEMP
    RETURN
    END

```


SECTION 5

LIST OF REFERENCES

- [1] M. L. Rehak , F. L. DiMaggio and I. S. Sandler, "Interactive approximations for a cavitating fluid around a floating structure," *Computers and Structures* V.21 No.21 (1985), pp.1159-1175.

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